Summary of MACRO results on exotic physics

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Abstract

MACRO was a multi-purpose experiment that took data from 1989 to 2000, at the underground Laboratory of Gran Sasso (Italy). MACRO gave important results/limits concerning: (i) the oscillation of atmospheric neutrinos, also in the non-conventional scenario of violations of Lorentz invariance, (ii) the searches for exotic particles (supermassive GUT magnetic monopoles, nuclearites, WIMPs), (iii) muon physics and astrophysics. A summary of the MACRO results will be presented and discussed, focusing the attention on the exotica searches.

1 Introduction

MACRO was a large area multipurpose underground detector [1] designed to search for rare events and rare phenomena in the cosmic radiation. The detector was located in Hall B of the underground Gran Sasso Laboratory (Italy). It was optimised to search for the supermassive magnetic monopoles [2, 3] predicted by Grand Unified Theories (GUT). The experiment obtained important results on atmospheric neutrino oscillations [4, 5, 6, 7, 8] and performed neutrino astronomy studies [9], indirect searches for WIMPs [10], search for low energy stellar gravitational collapse neutrinos [11], studies of the high energy underground muon flux (which is an indirect tool to study the primary cosmic ray composition and high energy hadronic interactions [12]), searches for fractionally charged particles (LIPs) [13] and other rare particles that may exist in the cosmic radiation.

The detector started data taking in 1989 and it was running until December 2000. The apparatus had global dimensions of $76.6 \times 12 \times 9.3\,\mathrm{m}^3$ and was composed of three sub-detectors: liquid scintillation counters, limited streamer tubes and nuclear track detectors. Each one of them could be used in "stand-alone" and in "combined" mode. It may be worth to stress that all the physics and astrophysics items listed in the 1984 proposal were covered and good results were obtained on each of them.

2 Atmospheric neutrino oscillations

MACRO detected ν_μ-induced muon events in 4 different topologies.

The *upthroughgoing muons* come from ν_μ interactions in the rock below the detector; the ν_μ's have a median energy of ~ 50 GeV.

Fig. 1 shows the zenith distribution of the measured 902 upthroughgoing muons (black circles) compared with two MonteCarlo (MC) predictions: the Bartol96 [14] flux with and without oscillations (the dashed and solid lines, respectively) and the Honda2001 flux [15]. The FLUKA MC predictions [16] agree perfectly with the Honda2001.

For a subsample of ~ 300 upthroughgoing events, we estimated the muon energy through Multiple Coulomb Scattering in the rock absorbers in the lower apparatus [7]. The evaluated resolution on E_ν is $\sim 100\%$. The parent neutrino path length is $L \sim 2R_E \cos\Theta$, where R_E is the Earth radius. Fig. 2 shows the ratio data/MC as a function of the estimated L/E_ν for the upthroughgoing muon sample. The black circles are data/Bartol96 MC (assuming no oscillations); the solid line is the oscillated MC prediction for

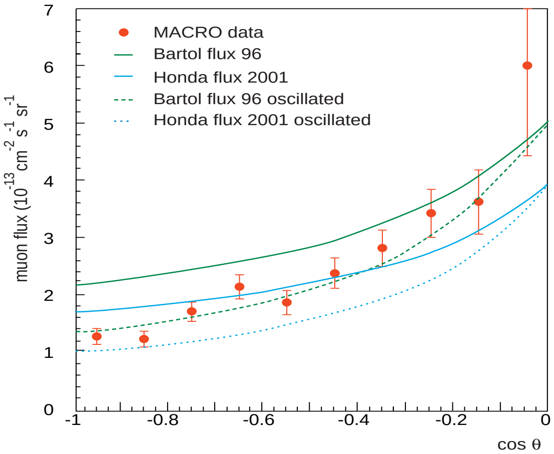

Figure 1: Comparison of the MACRO upward-throughgoing muons (black circles) with the predictions of the Bartol96 and of the Honda2001 MC oscillated and non oscillated fluxes (oscillation parameters $\Delta m^2 = 2.3 \cdot 10^{-3}$ eV^2 and $\sin^2 2\theta_m = 1$).

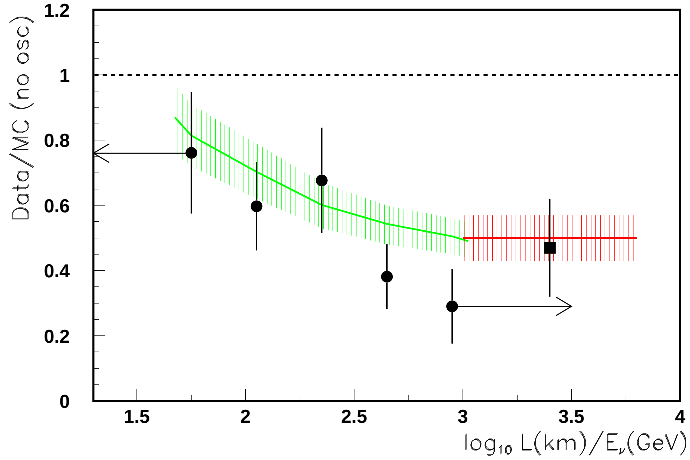

Figure 2: Ratio Data/MC$_{\text{no osc}}$ as a function of the estimated L/E_ν for the upthroughgoing muon sample (black points). The solid line is the MC expectation assuming $\Delta m^2 = 2.3 \cdot 10^{-3}$ eV^2 and $\sin^2 2\theta_m = 1$. The last point (black square) is obtained from the IU sample.

$\Delta m^2 = 2.3 \cdot 10^{-3}$ eV^2 and $\sin^2 2\theta_m = 1$. The shaded region represents the simulation uncertainties. The last point (black square) is obtained from semicontained upward going muons.

The low energy events (IU, $ID + UGS$ [5]) are produced by parent ν_μ interacting inside the lower detector, or by upgoing muons stopping in the detector. The median energy of the parent neutrino is $\sim 3 - 4$ GeV for all topologies. In both cases, the zenith distributions are in agreement with the oscillation prediction with the optimised parameters [8].

In order to reduce the effects of systematic uncertainties in the MC absolute fluxes we used the following three independent ratios [8]:

(i) High Energy data: vertical/horizontal ratio, $R_1 = N_{vert}/N_{hor}$

(ii) High Energy data: low energy/high energy ratio, $R_2 = N_{low}/N_{high}$

(iii) Low Energy data: $R_3 = (Data/MC)_{IU}/(Data/MC)_{ID+UGS}$

Combining the three independent results, the no oscillation hypothesis is ruled out at the $\sim 5\sigma$ level (6σ if the absolute values compared to the Bartol96 flux are used) [17].

To evaluate the hypothesis of oscillation for different values of Δm^2 and $\sin^2 2\theta_m$, the Feldman-Cousins [18] procedure was used and the corresponding 90% C.L. region for the $\nu_\mu \longleftrightarrow \nu_\tau$ oscillation is given in ref [8]. The best fit is reached at $\Delta m^2 = 2.3 \cdot 10^{-3}$ eV^2 and $\sin^2 2\theta_m = 1$.

2.1 Search for exotic contributions to atmospheric neutrino oscillations

MACRO searched for "exotic" contributions to standard mass-induced atmospheric neutrino oscillations, arising from a possible violation of Lorentz invariance (VLI) , using two different and complementary analyses. The first approach uses the low energy ($E_\nu < 28$ GeV) and the high energy ($E_\nu > 142$ GeV) samples. The mass neutrino oscillation parameters have the values given in Sect. 2 and we mapped the evolution of the χ^2 estimator in the plane of the VLI parameters Δv and $\sin^2 2\theta_v$. No χ^2 improvement was found, so we applied the Feldman-Cousins [18] method to determine 90% C.L. limits on the parameter: $|\Delta v| < 3 \cdot 10^{-25}$ [19].

The second approach exploits a data subsample characterised by intermediate neutrino energies. It is based on the maximum likelihood technique and considers the mass neutrino oscillation parameters varying in the 90% C.L. border [8]. The obtained 90% C.L. limit on the Δv parameter is also around 10^{-25} [20] .

3 Neutrinos from astrophysical sources

3.1 Search for astrophysical HE muon neutrinos

High energy ν_μ's are expected to come from several galactic and extra-galactic sources. An excess of events was searched for around the positions of known sources in 3° (half width) angular bins. The 90% C.L. upper limits on the muon fluxes from specific celestial sources were in the range $10^{-15} \div 10^{-14}$ cm^{-2} s^{-1} [21]. A search for time coincidences of the upgoing muons with γ-ray bursts was also made. No statistically significant time correlation was found [9].

A different analysis was made for the search for a diffuse astrophysical neutrino flux, using a dedicated method to select higher energy upthroughgoing muons. The flux upper limit was set at the level of $1.5 \cdot 10^{-14}$ cm^{-2} s^{-1} [22].

3.2 Indirect searches for WIMPs

Weakly Interacting Massive Particles (WIMPs) could be part of the galactic dark matter; they could be intercepted by celestial bodies, slowed down and trapped in their centres, where WIMPs and anti-WIMPs could annihilate and yield neutrinos of GeV or TeV energy, in small angular windows from their centres. One WIMP candidate is the lowest mass neutralino.

To look for a WIMP signal, we searched for upthroughgoing muons from the Earth centre, using $10° \div 15°$ cones around the Nadir; the 90% C.L. muon flux limits are $0.8 \div 1.4 \cdot 10^{-14}$ cm^{-2} s^{-1} [10]. These limits, when compared with the predictions of a supersymmetric model, eliminate a sizable range of parameters used in the model.

A similar procedure was used to search for ν_μ from the Sun: the muon upper limits are at the level of about $1.5 \div 2 \cdot 10^{-14}$ cm^{-2} s^{-1} [10].

3.3 Neutrinos from stellar gravitational collapses

A stellar gravitational collapse of the core of a massive star is expected to produce a large burst of all types of neutrinos and antineutrinos with energies of $5 \div 60$ MeV and with a duration of ~ 10 s. No stellar gravitational collapses in our Galaxy were observed from 1989 to 2000 [11].

4 Search for exotic particles

4.1 Search for GUT magnetic monopoles (MMs)

Supermassive magnetic monopoles predicted by Grand Unified Theories (GUT) of the electroweak and strong interactions should have masses $m_M \sim 10^{17}$ GeV.

MACRO was optimised to search for an isotropic flux of GUT MMs in the cosmic radiation. The three sub-detectors had sensitivities in different β regions, covering the velocity range $4 \cdot 10^{-5} < \beta < 1$. They allowed multiple signatures of the same rare event candidate. No candidates were found by any of the three subdetectors. Fig. 3 shows the 90% C.L. flux upper limits for $g = g_D$ poles (one unit of Dirac magnetic charge) plotted versus β [2] together with direct limits set by other experiments [23]. The MACRO MM direct limits are by far the best existing over a very wide range of β.

The interaction of the GUT monopole core with a nucleon can lead to a reaction in which the nucleon decays, $M + p \to M + e^+ + \pi^0$. MACRO dedicated an analysis procedure to detect nucleon decays induced by the passage of a GUT MM in the streamer tube system (a fast e^+ track from a slow ($\beta \sim 10^{-3}$) MM track). The 90% C.L. flux upper limits established by this search are at the level of $\sim 3 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1} for $10^{-4} \leq \beta \leq 0.5 \cdot 10^{-2}$; they are valid for catalysis cross sections $5 \cdot 10^2 < \sigma_{cat} < 10^3$ mb [3].

4.2 Search for nuclearites, Q-balls and LIPs

Strangelets should consist of aggregates of u, d and s quarks in almost equal proportion [24] and would have typical galactic velocities $\beta \sim 10^{-3}$. The MACRO 90% C.L. upper limits for an isotropic flux of nuclearites with $10^{-5} \leq \beta \leq 1$ was at the level of $1.5 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1} [25].

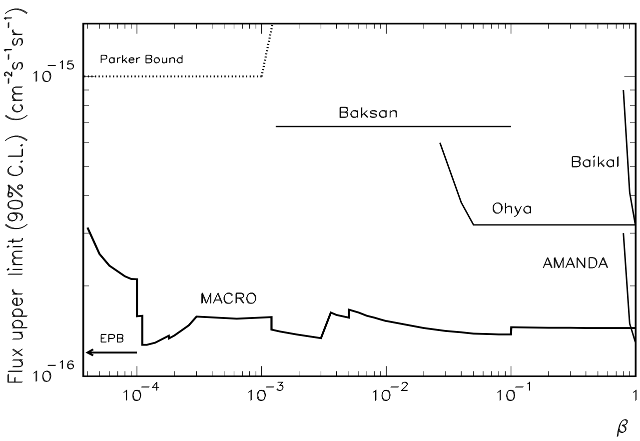

Figure 3: 90% C.L. upper limit obtained by MACRO for an isotropic flux of GUT MMs with $g = g_D$ compared with direct limits given by other experiments.

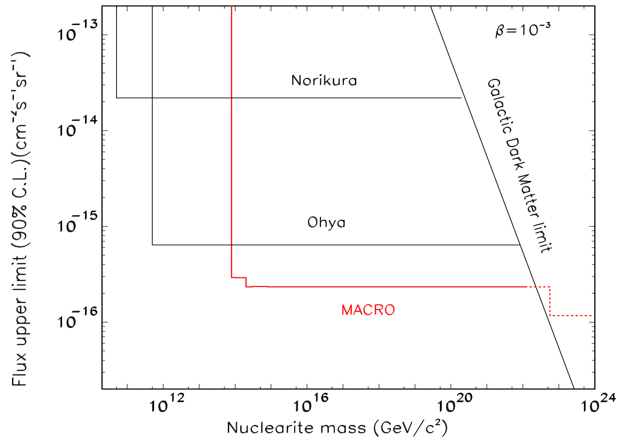

Figure 4: 90% C.L. upper limits versus mass for downgoing nuclearites with $\beta = 2 \cdot 10^{-3}$ at ground level. The MACRO limit for nuclearite masses larger than $5 \cdot 10^{22}$ GeV/c^2 has been extended and corresponds to an isotropic flux.

MACRO searched also for charged Q-balls (aggregates of squarks, sleptons and Higgs fields) [26], giving an upper limit of $\sim 10^{-16}$ cm^{-2} s^{-1} sr^{-1} [27].

Fractionally charged particles could be expected in Grand Unified Theories as deconfined quarks; the expected charges range from $Q = e/5$ to $Q = 2/3e$. LIPs should release a fraction $(Q/e)^2$ of the energy deposited by a muon traversing a medium. The 90% C.L. flux upper limits for LIPs with charges $e/3$, $2/3e$ and $e/5$ are at the level of 10^{-15} cm^{-2} s^{-1} sr^{-1} [13].

5 Conclusions

– Standard atmospheric ν_μ oscillations: no-oscillation hypothesis ruled out at $5 \div 6\sigma$.
Best fit parameters: $\Delta m^2 = 2.3 \cdot 10^{-3}$ eV^2 and $\sin^2 2\theta_m = 1$.
– VLI: $|\Delta_v|$ upper limits of the order of 10^{-25}.
– MM search: upper flux limit of $1.4 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1} for $4 \cdot 10^{-5} < \beta < 1$.
– Nuclearite search: upper flux limit of 10^{-16} cm^{-2} s^{-1} sr^{-1} for $\beta \simeq 10^{-3}$.
– Charged Q-balls search: upper flux limit of $\sim 10^{-16}$ cm^{-2} s^{-1} sr^{-1}.
– WIMP search: upper flux limit of $\sim 10^{-14}$ cm^{-2} s^{-1} sr^{-1}.
– LIP search: upper flux limit of $6.1 \cdot 10^{-16}$ cm^{-2} s^{-1} sr^{-1}.

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